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Moving Towards Virtual Manufacturing

Delivering Metal Forming Properties with Multi-Scale Modelling

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Knowledge of appropriate and accurate material properties constitutes a substantial challenge in the simulation of manufacturing processes. The appeal of multi-scale modelling lies in the quantitative link it provides between the properties we can observe on the macro-scale and the key features in the microstructure that lie at the physical origin of those properties. Fibre-reinforced composites have certain preferential fibre orientations that increase the strength in these directions. Likewise, metals consist of micrometer-sized crystals of one or several phases with specific preferential orientations, giving it direction-dependent properties. For composites and metals alike, the production process controls the initial microstructure, and consequently also the properties that control the behaviour in subsequent manufacturing steps.

On top of this, the properties themselves often change drastically throughout the manufacturing process chain. This adds a level of complexity for reliable through-process design. Examples are ample; think of welding processes and heat treatments of metals, sintering of ceramic materials, and fiber impregnation in composite manufacturing. Also local variations within a single part during processing may lead to significant variations in properties. The concept of a given part having homogeneous properties, as is generally assumed providing material input data, may in fact be far from reality. Relying on homogeneous material properties in simulation may severely limit the relevance and usefulness of manufacturing CAE. Concurrently with the global race to increase the functionality within a single manufactured part, the variation of properties in intermediate and final parts inevitably increases. Of course, it is desirable to properly account for such gradients in the designs and manufacturing simulations, but only at a reasonable cost. Multi-scale modelling responds to these conflicting needs, as it intrinsically provides a two-way coupling across the scales. In essence, the multi-scale model answers two questions simultaneously: how are the local processing conditions affecting the microstructure, and what are the local properties resulting from the microstructure?

Another critical issue in forming simulation is the availability of the relevant material data. Forming properties are directly measured by mechanical testing; the tensile test is by far the most widespread test, having appropriate test standards for nearly all material classes. However, forming conditions are often drastically different from those of the tensile test. More advanced mechanical testing lacks standardization and bears with it a high cost. While there is evidently a need for more accurate material models in forming process simulation, any additional complexity to adopt and calibrate such models poses a stumbling block. Multi-scale modelling can resolve this dilemma by providing the relevant properties based on microstructural measurement. When considering the modelling of the variability of material properties, the scarcity of material data is evidently more stringent. Also in this case, microstructure-based multi-scale modelling is an attractive alternative to elaborate mechanical testing campaigns.

An Insight in Multi-Scale Modelling for Metal Forming Application

Multi-scale models start from a model representation of the material's microstructure including the main microstructural features that determine the macroscopic properties of interest. In the field of metal forming (see Figure 1), preferred crystal orientations and distribution of multiple phase (for metals that consists of more than one phase) are of paramount importance. This microstructural information is obtained by diffraction measurements techniques using X-rays or electrons. These techniques are already widespread in the metal producing industries for internal quality control purposes. The involved length scale, being the size of a single metallic crystal, is in the order of 10 micrometer.

The first multi-scale model for metal deformation had already been proposed some time before the computer era, by Taylor in 1938. The Taylor model is still today widely used as a reference multiscale model. State-of-the-art multi-scale models incorporate the interaction between crystals in the microstructure. Over the past decades, a large variety of multi-scale modelling approaches has been developed, with different mathematical assumptions to couple small-scale physical phenomena with the homogenized macro behaviour; a comparison of accuracy for some of these models is made in (Eyckens et al., 2011). While an in-depth overview and discussion would be out of scope for this introductory article, it may be noteworthy to mention that the results presented in the following sections are obtained with one of the most computationally efficient multi-scale models, for which a typical simulation takes seconds or at most a few minutes on a standard PC.

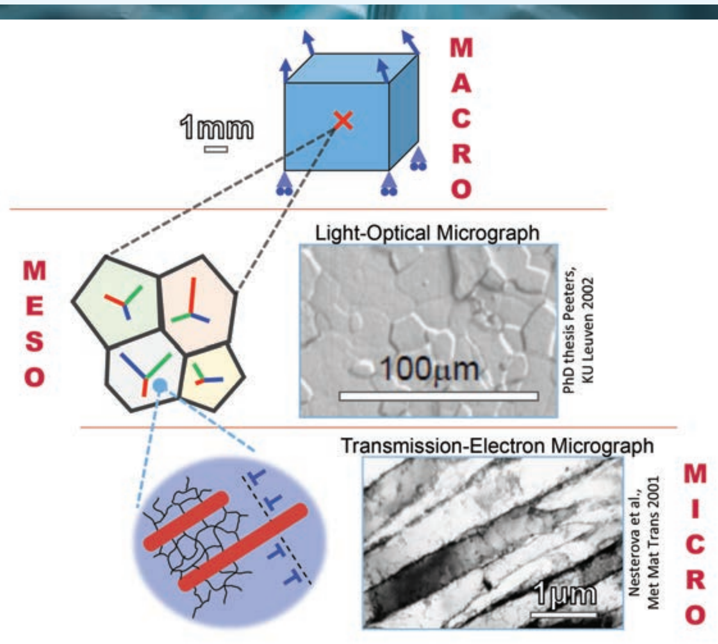

Figure 1: The properties at the macroscale are determined by microstructure at lower length scales. In the field of metal forming, the preferential orientations of metallic crystals play a paramount role in the anisotropic (direction-dependent) properties on the macroscale.

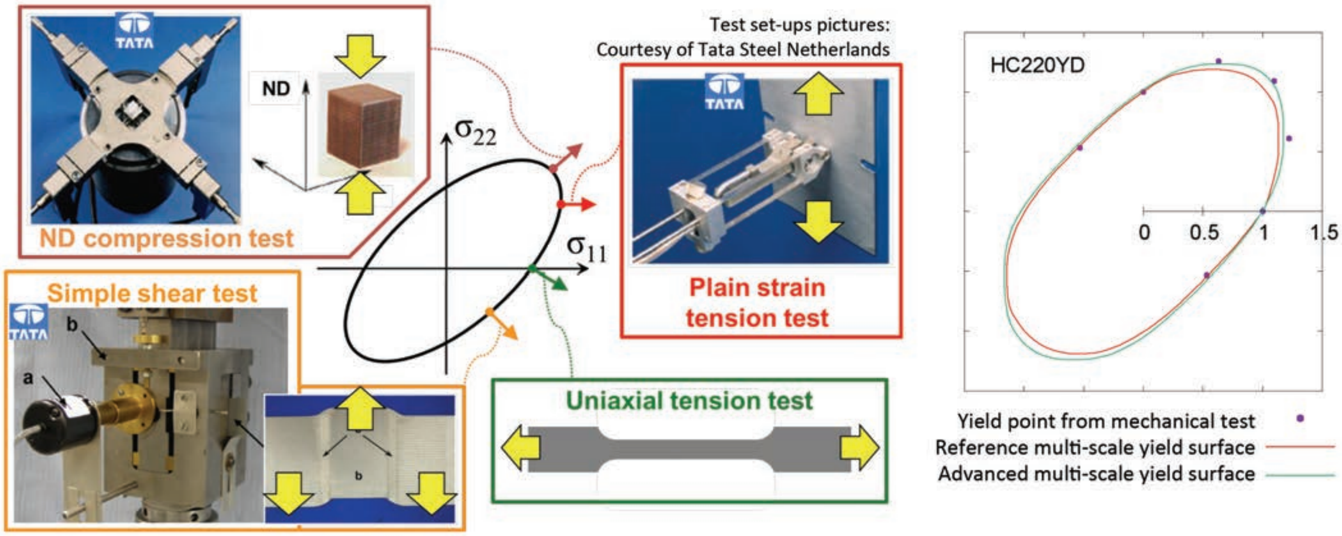

Figure 2 : A variety of yield points can be measured by employing different test set-ups (left), and by testing in multiple directions. On the right side, yield points and multi-scale yield loci are compared for the hot-dip galvanised high strength steel HC220YD.

State-of-the-art multi-scale models may also involve multiple lower length scales, as illustrated in Figure 1. For instance, the hardening phenomena resulting from dislocation interaction on the sub-micrometer scale may also be incorporated. Multi-stage forming processes on the other hand typically exhibit changes of the local strain paths, leading to drastic changes in microstructure and ultimately, in hardening phenomena such as the Bauschinger and cross effects. These hardening phenomena can be incorporated in the multi-scale model framework via modelling of the substructure, i.e. the dislocation entanglement that continuously develops during deformation. In the following sections however, we'll focus on single-stage forming simulations. In this case, tensile test data in a single direction is sufficient for calibration of strain hardening.

Reliability of Multi-Scale Material Data

Let's first have a closer look at the practical application of multi-scale modelling in forming process simulation. A key model concept in metal forming simulation is the yield surface, which collects all possible stress conditions that induce plastic (permanent) deformation. Each combination of mechanical test set-up and loading direction can directly measure a single point of the yield surface (Vegter & An, 2008), as is illustrated in Figure 2. As a side note: only a small part of the entire yield surface is shown in this figure because it is in fact a 5-dimensional object. The right graph of Figure 2 gives an example for a high strength steel: the measurement data from 7 different mechanical tests give as many yield surface points. The full lines are yield surfaces generated by multiscale modelling; these are generated from measurement of the microstructure only. State-of-the-art multi-scale modelling (green line) is able to accurately represent the yield surface, while the reference multi-scale model (Taylor model – red line) is of substantially lower quality. The example material is quite representative, so advanced multi-scale modelling does offer a reliable means to represent the yield surface accurately. Consequently, multi-scale modelling has an interesting potential to become an integral part of future material cards for high quality simulations.

Tackling Material Property Variability with Multi-Scale Modelling

High-confidence robust process design requires property variability data in addition to nominal properties. Let's look at another example of anisotropic property: the so-called r-value (also known as Lankford coefficient), which is a measure of the resistance to sheet thinning during tensile loading with extensive plastic elongation. A sheet material with high r-value will show more contraction in the in-plane width direction as compared to the sheet thickness direction. In stamping operations, this property controls final product thickness within the zones that are subjected to uniaxial stresses, being similar conditions as the tensile test. For most materials, the r-value is anisotropic: it clearly depends on the tensile direction with respect to the rolling direction. Figure 3 compares nominal properties and variability across 48 coils from a single order (identical coil dimensions and production route) of a deep drawing quality grade steel. At first sight, very comparable material date is obtained by direct measurement (via mechanical testing) and by advanced multi-scale modelling. The multi-scale approach has as advantage that all properties of a certain coil are obtained from a single (microstructural) measurement. On the other hand, properties measured by a series of mechanical tests may overestimate the intrinsic material variability, because for each coil many tests on different samples are involved. This may lead to artefacts in material variability: during machining, variations in test sample edge quality may occur, while during tensile testing variations in ambient temperature (even by a few

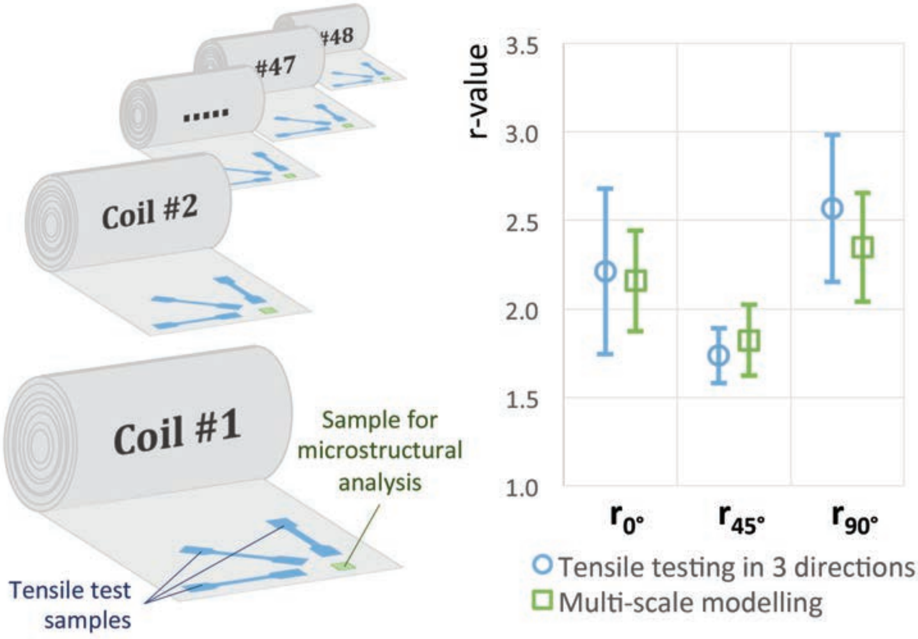

Figure 3: Inter-coil variability of r-value properties. For a DX54D+Z forming steel, variability across 48 coils is evaluated by tensile testing, and by microstructure-based multi-scale modelling. In the graph to the right, variability in r-values is expressed by nominal values (symbols) and ranges of ± 3 times standard deviations (vertical bars).

degrees) may increase variability. This explains the somewhat larger spread that is seen for the mechanical tests.

In terms of excessive thinning, the most critical tensile direction is the one having the lowest r-value, which is 45° to the rolling direction for the steel grade at hand. Variability data is a key piece of information to be able to set the design window for stamping processes on this material with a high degree of reliability. The small variability of r45° (compared to r0° and r90°) of this material is especially relevant in the context of part reject rates due to excessive thinning.

Multi-Scale Finite Element Sase Study

The case study on aluminum cup deep drawing, presented in Figure 4, illustrates the application of advanced multi-scale material in FE simulation (Gawad et al., 2015). Starting from a circular blank, a round cup is deep drawn in a single forming stage. Despite the axisymmetry of process and blank, the draw-in is never uniform in practice, due to the direction-dependency of the blank properties. After full draw-in, so-called ears are formed. Apart from being immediately relevant for the canning industry as a potential source of material waste, the accurate prediction of the earing pattern is also a widespread benchmark for material modelling in automotive steel and aluminum alloys. The sheet anisotropy originates from the thermomechanical processing history, being the hot and cold rolling and the heat treatments of the coil from which the circular blank was cut. The properties of such blank material have two symmetry planes: along and across the rolling direction (RD), which translates itself in an FE simulation of a quarter cup with symmetry boundary conditions. In present case study, an AA6016 outer panel automotive alloy was studied. Experimentally, ears at 0° and 90° to RD are observed. Neglecting material direction-dependent properties (simulation with the isotropic von Mises yield locus), simulation predicts a quasi-uniform cup height (small, irregular oscillations are due to mesh discretization).

The material anisotropy was accounted for in FE simulation through the BBC2008 yield locus proposed by Banabic. A total of 9 testing conditions are required for calibration: tensile testing in 7 different directions, and additionally two advanced mechanical tests (hydraulic bulge test and stack compression test) for the equibiaxial condition. The traditional calibration strategy of using measurement data from this series of mechanical tests was compared to a multi-scale calibration approach. In the latter, multi-scale approach, a single microstructure measurement (texture measurement of crystal orientation distribution via X-ray diffraction) together with tensile test data along a single direction (RD), was sufficient input data to calibrate the multi-scale model, which subsequently produced all material law data of the

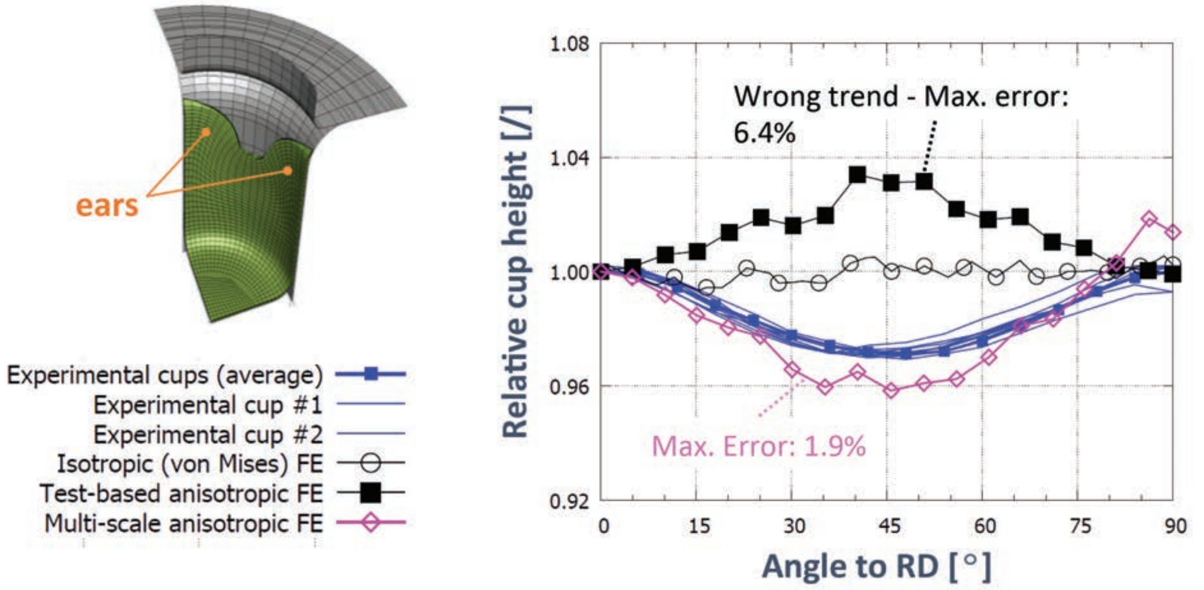

Figure 4: Material anisotropy causes earing in the deep drawing of a circular blank into a round cup (left: one quarter of FE model shown). For a AA6016-T4 aluminum blank, ears develop at 0° and 90° to rolling direction (RD). FE simulation with multi-scale calibration of yield locus delivers a highly accurate result, while calibration by mechanical tests leads to a wrong trend in this case.

yield locus. Comparison of the simulation results (right side of Figure 4) leads to a remarkable observation: whereas the multi-scale calibration shows outstanding accuracy of earing prediction, the traditional test-based approach predicts a wrong trend in earing profile. The key to the wrong trend of the mechanical test-based prediction relates to the relatively small differences in yield stress between the various tensile test directions for this particular aluminum alloy: these differences are on one hand too small to be identified according to tensile test procedures described in international norms, yet significant enough to determine the experimentally observed earing pattern. As the multi-scale calibration strategy relies on microstructural measurement to retrieve all properties including yield stresses in different directions, it is able to deliver this highly reliable result. ■

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Philip Eyckens obtained a PhD at the KU Leuven, Department of Materials Engineering, in the areas of sheet metal formability modelling and incremental sheet forming processes. As post-doctoral researcher, he has gained expertise on microstructure-based modelling of hardening with strain path changes and generic multi-scale simulation of metal forming processes. His current professional focus is on research valorization in the metal forming industries. Philip is a member of the NAFEMS Manufacturing Process Simulation Working Group. He can be reached at
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